

THE DENSITY AND SPECTRAL ENERGY DISTRIBUTIONS OF RED GALAXIES AT $Z \sim 3.7$ GABRIEL B. BRAMMER¹ AND PIETER G. VAN DOKKUM¹*Accepted for publication in ApJL*

ABSTRACT

We use the deep NIR imaging of the FIRES survey to investigate trends with redshift of the properties of galaxies selected to have strong Balmer/4000 Å breaks at $2 < z < 4.5$. Analogous to the $J - K > 1.3$ (AB) color criterion designed to select red galaxies at $z > 2$, we propose two color criteria, $J - H > 0.9$ and $H - K > 0.9$, to select red galaxies in two redshift bins at $2 < z < 3$ and $3 < z < 4.5$, respectively. From the FIRES catalogs of the HDF-S (4.7 arcmin²) and MS 1054-03 (26.3 arcmin²) fields, we find 18 galaxies with $\langle z_{\text{phot}} \rangle = 2.4$ that satisfy $J_s - H > 0.9$; $H < 23.4$ and 23 galaxies with $\langle z_{\text{phot}} \rangle = 3.7$ that satisfy $H - K_s > 0.9$; $K_s < 24.6$, where the flux limits are chosen to match the limiting rest-frame luminosities at the different median redshifts of the two samples. The space densities of the $J_s - H$ and $H - K_s$ samples are $1.5 \pm 0.5 \times 10^{-4}$ and $1.2 \pm 0.4 \times 10^{-4}$ Mpc⁻³, respectively. The rest-frame $U - B$ colors of galaxies in both samples are similarly red (as expected from the definition of the color criteria), but the rest-frame UV properties are different: galaxies in the higher-redshift $H - K_s$ selected sample have blue NUV-optical colors and UV slopes similar to those of Lyman Break Galaxies, while the $J_s - H$ galaxies are generally red over the entire wavelength range observed. Synthetic template fits indicate that the distinct rest-NUV properties of the two samples are primarily a result of dust: we find $\langle A_V \rangle_{JH} = 1$ mag and $\langle A_V \rangle_{HK} = 0.2$ mag. The median stellar mass determined from the template fits decreases by a factor of ~ 5 from $z = 2.4$ to 3.7 , which, coupled with the fact that the space density of such galaxies remains roughly constant, may imply that the stellar mass density in red galaxies decreases by a similar factor over this redshift range.

Subject headings: cosmology: observations — galaxies: evolution — galaxies: formation

1. INTRODUCTION

Over the last few years, the study of galaxies with red rest-frame optical colors has been extended to ever-increasing redshifts. While the selection of galaxies based on their rest-frame UV emission (e.g. the Lyman break technique; Steidel & Hamilton 1993) has enabled the detailed study of young galaxies at high redshift for some time, it is only with the more recent advent of efficient, large-scale detectors in the near-IR that large numbers of galaxies with redder rest-frame colors have been discovered at early cosmic epochs (Franx et al. 2003; van Dokkum et al. 2003). Red galaxies with typically very low UV fluxes make up 80% of the mass contained in the most massive galaxies (van Dokkum et al. 2006) and 25-75% of the total mass in galaxies at $2 < z < 3$ (Papovich et al. 2006; Marchesini et al. 2006), and thus provide critical constraints on theoretical models of galaxy formation and evolution (Somerville et al. 2004; Nagamine et al. 2005).

A proven technique for selecting galaxies with red rest-frame optical colors is the $J_s - K_s > 1.3$ criterion ($J - K_{\text{Vega}} > 2.3$; Franx et al. 2003), which relies on the Balmer/4000 Å break redshifted into the J band for redshifts $z > 2$. Galaxies selected using this technique comprise a heterogeneous population showing a broad range in dust properties, luminosity-weighted ages, and star-formation rates (Förster-Schreiber et al. 2004; Labbé et al. 2005; Papovich et al. 2006; Kriek et al. 2006b).

In this Letter, we extend the study of red galax-

ies to redshifts $z > 3$, and we compare the number and properties of red galaxies at $z \sim 3.5$ to those at $z \sim 2.5$ using uniform color selection criteria based on the Balmer/4000 Å break redshifted into the H and J_s bands, respectively. While there is typically a tail of sources extending beyond $z > 3.5$ in $J - K$ selected samples (e.g. Förster-Schreiber et al. 2004), there have been no systematic studies comparing the numbers and properties of red galaxies at the extremes of the broad $J - K$ redshift selection window. We adopt $H_0 = 70$ km/s, $\Omega_m = 0.3$, and $\Omega_\Lambda = 0.7$. All magnitudes are given in the AB system.

2. COLOR SELECTION OF RED GALAXIES

The top panel of Fig. 1 shows the observed $J_s - K_s$ color of Bruzual & Charlot (2003) template spectra over $0 < z < 5$. At a given redshift, $J_s - K_s$ is reddest for the oldest template because the strength of the Balmer/4000 Å break increases as a stellar population ages. Based on the figure, $J_s - K_s > 1.3$ should select galaxies at $z > 2$ that are either dominated by an evolved stellar population or are highly reddened by dust—the so-called “distant red galaxies”, or DRGs (Franx et al. 2003). A number of DRGs have been spectroscopically confirmed (van Dokkum et al. 2003; Kriek et al. 2006a,b) at $z > 2$, and large photometric samples of DRGs are found to have $1.5 \lesssim z_{\text{phot}} \lesssim 3.5$ (Förster-Schreiber et al. 2004; Papovich et al. 2006; Quadri et al. 2006).

Because DRGs have a fairly broad redshift distribution, the rest-frame properties of galaxies satisfying the color criterion to a given magnitude limit in a particular selection band change with redshift in three important ways. First, the limiting absolute magnitude in the selection band becomes brighter with increasing redshift for

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a fixed survey depth, probing sharply decreasing source densities at the bright end of the steep luminosity function. Second, the rest wavelength of the selection band decreases with increasing redshift, probing wavelengths where the scatter in M/L_λ is large. Finally, the rest-frame color—essentially the type of galaxy selected—changes with redshift because the Balmer/4000 Å break is narrow in wavelength compared to the spacing between the J_s and K_s filters and because the spectral slope is not the same on both sides of the break for galaxies older than ~ 100 Myr. Together, these effects make it very difficult to compare DRG properties at different redshifts.

The bottom panel of Fig. 1 demonstrates how splitting the $J-K$ criterion into two should divide DRGs into two redshift bins,

$$\begin{aligned} J_s - H > 0.9 : z > 2 \\ H - K_s > 0.9 : z > 3, \end{aligned} \quad (1)$$

mitigating the problems described above that prevent direct analysis of the variation of red galaxy properties with redshift. The wavelength baselines of the two NIR colors are similar enough that the same color limit can be used for both criteria to select identical rest-frame powerlaw spectral slopes. The criteria of Equation 1 are adopted analogous to $J_s - K_s > 1.3$ to select against low- z interlopers, while the selection efficiency of the $J_s - H$ and $H - K_s$ criteria may be further enhanced by the fact that those colors are steeper functions of redshift at the low- z selection boundaries than $J_s - K_s$.

Alternatively, one could select samples of galaxies based on their rest-frame properties estimated using distances determined from the galaxies' photometric redshifts. We note, however, that the $z_{\text{phot}} - z_{\text{spec}}$ calibration is poorly determined at $z > 3$, and therefore relying on photometric redshifts alone introduces large uncertainties in the analysis at high redshift. Furthermore, by working in the observed frame, the results can be easily verified by others independent of photometric redshift or analysis techniques.

3. DATA

We use the deep optical+NIR photometry of the FIRES survey (Franx et al. 2000) to select red galaxies at $z > 2$ based on the two NIR color criteria described above. Details of the data reduction and K -selected source catalogs of the two fields of the survey, HDF-S (4.7 arcmin^2) and MS 1054-03 (26.3 arcmin^2), can be found in Labbé et al. (2003) and Förster Schreiber et al. (2006), respectively. Briefly, the combined catalog of the two fields contains HST $U_{300}B_{450}$ (HDFS-S), $V_{606}I_{814}$ (both fields), ground-based UBV (MS 1054-03) and ISAAC- J_sHK_s (both fields) photometry, along with photometric redshifts determined following the procedure described by Rudnick et al. (2001, 2003). Details of the accuracy of the photometric redshifts in these fields are given in Labbé et al. (2003) and Förster Schreiber et al. (2006). The combined catalog depth is limited by the shallower MS 1054-03 observations. At $K_s = 24.6$, the combined catalog is $\sim 90\%$ complete and sources in the MS 1054-03 catalog have $(S/N)_K = 5 - 7$. The FIRES dataset provides a unique opportunity to select red galaxies at $z > 3.5$ —even the brightest of which should still be quite faint in K —since there are no other currently available

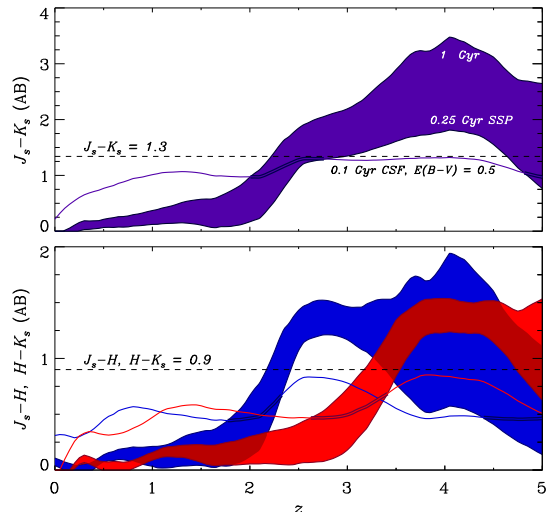


FIG. 1.— *Top*: Evolution of $J_s - K_s$ color with redshift. The dashed line shows the DRG criterion of Franx et al. (2003) designed to select passively-evolving galaxies at $z > 2$. *Bottom*: $J_s - H$ (blue) and $H - K_s$ (red) vs. z . The dashed line indicates the selection criteria used in this Letter, which are analogous to the DRG color selection but that divide the DRG sample into two redshift bins. The shaded bands indicate the range of colors of dust-free Bruzual & Charlot (2003) passively evolving templates with ages between 0.25 and 1.0 Gyr. The thin lines correspond to a template with a constant star formation rate with age 0.1 Gyr and $E(B-V) = 0.5$, showing that moderately reddened starbursts at low redshift are not expected to significantly contaminate the $z > 2$ NIR-selected galaxy samples.

surveys of comparable depth in all three JHK NIR filters.

4. DENSITIES

From the combined FIRES catalog we find 18 sources that satisfy $J_s - H > 0.9$; $H < 23.4$ and 23 sources with $H - K_s > 0.9$; $K_s < 24.6$. The limiting magnitude in H was chosen such that the rest-frame limiting magnitude redward of the Balmer/4000 Å break is the same for both samples, and its value was determined based on the ratio of the luminosity distances at the median redshifts of the two samples. The number of selected sources correspond to combined (HDF-S-only) surface densities and Poisson errors of 0.58 ± 0.18 (0.63 ± 0.37) and 0.74 ± 0.19 (0.42 ± 0.30) arcmin^{-2} for the $J_s - H$ and $H - K_s$ selected samples, respectively. The photometric redshift distributions of the NIR selected sources are shown in Fig. 2. The $J_s - H$ sample has $z_{\text{phot}} = 2.4 \pm 0.3$ ($1-\sigma$ range) and 16/18 galaxies also satisfy $J_s - K_s > 1.3$. For the $H - K_s$ sample, $z_{\text{phot}} = 3.9 \pm 1.0$ and 15/23 galaxies satisfy $J_s - K_s > 1.3$.

If we consider comoving volumes bounded by tophat redshift distributions of $2 < z_{\text{phot}} < 3$ and $3 < z_{\text{phot}} < 4.5$, the area-weighted space densities and associated Poisson errors of the $J_s - H$ and $H - K_s$ samples are $1.5 \pm 0.5 \times 10^{-4}$ and $1.2 \pm 0.4 \times 10^{-4} \text{ Mpc}^{-3}$, respectively. Therefore, the space density of a flux-limited sample of red galaxies remains constant within the errors from $\langle z \rangle_{\text{JH}} \sim 2.4$ to $\langle z \rangle_{\text{HK}} \sim 3.7$. We note that the total survey area discussed here is relatively small and that our result is likely subject to cosmic variance, especially in light of recent studies that show that red galaxies at $z > 2$ are strongly clustered (Daddi et al.

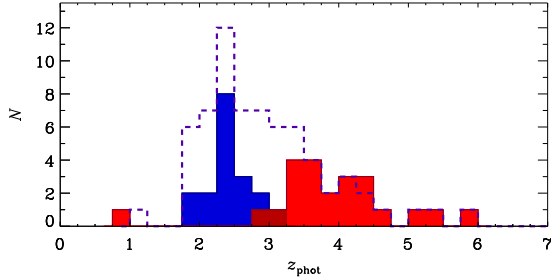


FIG. 2.— Photometric redshift distribution of galaxies in the FIRES fields with $J_s - H > 0.9$; $H < 23.4$ (blue) and $H - K_s > 0.9$; $K_s < 24.6$ (red). Although the samples show a small overlap in redshift space, no galaxy meets both selection criteria. For comparison, the dotted line shows the redshift distribution of galaxies satisfying $J_s - K_s > 1.3$ and $K_s < 24.6$.

2003; Quadri et al. 2006).

5. REST FRAME SEDS

Although there is no appreciable change in the *number* of galaxies selected to have strong Balmer/4000 Å breaks from $z \sim 2.4$ to $z \sim 3.7$, their properties are quite different. Fig. 3 shows the spectral energy distributions (SEDs) of the two galaxy samples shifted to the rest-frame. The $J_s - H$ galaxies typically have red rest-frame UV-optical colors and a fairly flat rest-UV spectrum, consistent with previous studies of DRGs in the redshift range $2 < z < 3$ (Förster-Schreiber et al. 2004). In contrast, the higher-redshift $H - K_s$ galaxies generally have blue UV-optical colors. The spectral slopes of the two samples through the Balmer/4000 Å break are similar for the two samples, confirming that the NIR color criteria proposed here select galaxies with similar $(U - B)_{\text{rest}}$ colors over $2 < z < 4.5$.

We quantify the spectral shapes of the SEDs using the rest-frame UV power-law slope, $F_\lambda \propto \lambda^\beta$ (Calzetti et al. 1994), measured from a best-fit Bruzual & Charlot (2003) template with an exponentially decaying star formation rate ($\tau = 300$ Myr) and solar metallicity. The template fits to the broadband photometry hold the redshift fixed to the catalog z_{phot} values, allow ages between 0.1 Myr and the age of the universe at z_{phot} and allow $A_V = 0 - 3$ mag following the extinction law of Calzetti et al. (2000). Corrections for Ly α forest absorption are applied following Madau (1995). The distributions of β for the two galaxy samples are shown in Fig. 3. The distribution is quite flat for the $J_s - H$ sample—similar to the distribution seen for a large sample of massive DRGs by van Dokkum et al. (2006). In contrast, the distribution of β for the $H - K_s$ sample shows a peak at $\beta \sim -2$, values similar to those found by Adelberger & Steidel (2000) for UV-selected galaxies and to the sample of massive Lyman break galaxies (LBGs) discussed by van Dokkum et al. (2006).

Of the 12 galaxies in the $H - K$ sample that have z_{phot} in the range $2.7 < z < 3.4$ or $3.9 < z < 4.5$, 10 have synthetic U_nGRI colors integrated from the best-fit templates that satisfy the U or G dropout LBG color criteria at those redshifts proposed by Steidel et al. (1999). However, 8 of those 10 galaxies with LBG colors have $R > 25.5$, too faint to be included in typical spectroscopic samples of LBGs.

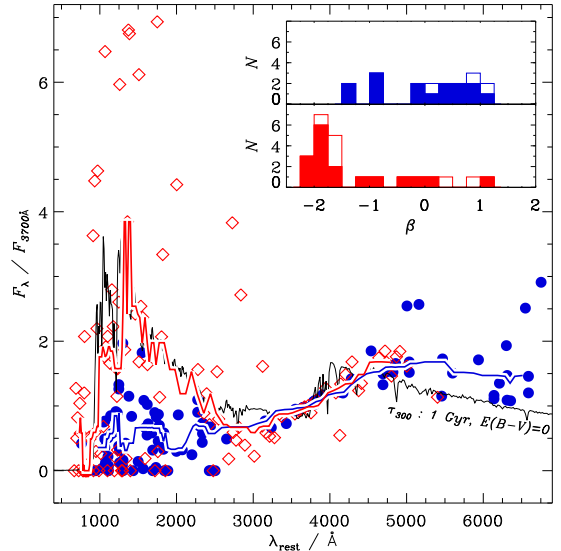


FIG. 3.— Rest-frame SEDs of the $J_s - H$ (blue circles) and $H - K_s$ (red diamonds) galaxy samples limited to $2 < z_{\text{phot}} < 3$ and $3 < z_{\text{phot}} < 4.5$, respectively. The SEDs are normalized to the flux at $\lambda_{\text{rest}} = 3700$ Å determined from a linear interpolation between the two nearest filters in the rest frame. The solid red and blue lines indicate a running median of the 10 neighboring points for the two samples. An unreddened 1 Gyr old τ_{300} template is shown for reference. The similarity of the SED slopes at the Balmer/4000 Å break demonstrates how the two color criteria are matched to select similar rest-frame spectral shapes at two different redshifts. *Inset*: distribution of the synthetic rest-frame UV spectral slope, β . The thin histograms correspond to the entire samples, while the filled histograms are for sources that fall within the $2 < z_{\text{phot}} < 3$ and $3 < z_{\text{phot}} < 4.5$ comparison ranges. With few exceptions, the higher redshift galaxies in the $H - K_s$ sample have UV-optical colors that are significantly bluer than those of the $J_s - H$ selected galaxies at lower redshift.

6. DISCUSSION

We have shown that we can efficiently select $z \sim 3.7$ galaxies in the near-IR with the simple color criterion $H - K > 0.9$. The samples described here indicate that the rest-frame UV-optical SEDs of galaxies selected to have strong Balmer/4000 Å breaks are significantly different at $z \sim 2.4$ and $z \sim 3.7$: galaxies in the higher redshift sample have a median NUV/optical flux ratio 2–4 times greater than that of the galaxies at $z \sim 2.4$. Finding evolution in the properties of galaxies over the ~ 1 Gyr between $z = 2.4 - 3.7$, which at the distant end is only 1.7 Gyr after the Big Bang, is in itself not surprising, as the spectral evolution is rapid at these redshifts for galaxies with a broad range of formation redshifts and subsequent star formation histories. What is interesting is that the galaxies in both samples were selected to have similarly strong Balmer/4000 Å breaks, indicating the presence of an evolved stellar population that itself would not be a likely source for the strong NUV component of the $z \sim 3.7$ SEDs. A two-burst model whose optical SED is dominated by an evolved stellar population but that also contains a young component that supplies the UV flux could explain the $z \sim 3.7$ SEDs. Though two-component model fits are beyond the scope of this Letter, there have been other observations of red galaxies at high- z suggesting that composite populations are appropriate, both from SED modelling (Yan et al. 2004)

and from observations of distinct UV and optical galaxy morphologies (Toft et al. 2005) of such galaxies.

Our τ_{300} template fits suggest that dust is the primary source of the difference in spectral shape shown in Fig. 3. Both samples have a median template age of ~ 1 Gyr, while the median dust extinction decreases from $A_V = 1$ to 0.2 mag going from the $J_s - H$ to the $H - K_s$ sample. In general one expects the dust content of galaxies, along with the metal content, to increase with time, qualitatively consistent with the analysis presented here. It is difficult to quantitatively compare our results to theoretical models of galaxy formation since such models typically rely on ad hoc treatments of dust absorption (e.g. Croton et al. 2006). Interestingly, our results may be qualitatively consistent with the redshift distribution of submillimeter-selected galaxies. Although still quite uncertain, there is evidence that the number of very dusty, luminous galaxies drops significantly from $z \sim 2.4$ to $z \sim 3.7$ (Chapman et al. 2005).

The normalization of our population synthesis fits provides a rough estimate of the stellar mass of each galaxy in the sample. With our photometry sampling only the rest-frame UV-optical light of the galaxies in our sample at $z > 2$, the stellar mass fits are uncertain to factors of > 2 due to uncertainties in z_{phot} and in the IMF and to model degeneracies between age, dust, metallicity, and star formation history. With those caveats in mind, our template fits imply that the median stellar mass of red galaxies decreases by a factor of ~ 5 from $z \sim 2.4$ to $z \sim 3.7$. While the uncertainties are large for the masses of individual galaxies, a Mann-Whitney test on the distribution of masses suggests that the difference in the median masses of the two samples is significant at the 99% confidence level. Erb et al. (2006) observe a similar trend in the mass of LBGs: the average dynamical and stellar masses of $z \sim 3$ LBGs are a factor of 2 smaller than for LBGs at $z \sim 2$. We note here that the $H - K$ galaxies are not necessarily direct progenitors of the $J - H$ galaxies, just as LBGs at $z = 4$ are not necessarily progenitors of LBGs at $z = 2$. Many of the $H - K$ galaxies could fade below our magnitude limit after ~ 1 Gyr; conversely, many of the $J - H$ galaxies could have been much bluer 1 Gyr previously.

Since the space densities of the $J_s - H$ and $H - K_s$ sam-

ples are statistically equivalent, a decrease in the median stellar mass in the higher redshift sample, if real, would indicate a decrease in the stellar mass density of galaxies with evolved stellar populations. This may be consistent with the results of Kriek et al. (2006b), who find that the ages of apparently passive galaxies at $z \sim 2.3$ (which make up 45% of their K -selected sample) are typically $\lesssim 1$ Gyr. It seems unlikely that many of the $z > 3$ progenitors of these galaxies were already “red and dead”. On the other hand, this result may be difficult to reconcile with the existence of a significant population of $M_* > 10^{11} M_\odot$ galaxies at $z > 6$, as may be implied by the source described by Mobasher et al. (2005). Furthermore, the best fit Bruzual & Charlot (2003) $z = 6.5$ template of the Mobasher et al. (2005) source has $\beta \sim 2$ and would be an outlier even at $z \sim 3.7$ compared to the sources in our $H - K$ sample.

Clearly, much further work is required to fully understand how the properties of red galaxies change with time at $z > 2$. The differences shown in Fig. 3 are model independent, to the extent that the photometric redshifts approximate the true redshifts, but the results above based on template fits are quite uncertain. The addition of *Spitzer* photometry would better constrain the stellar mass contained in these galaxies (Wuyts et al. 2006). The brightest galaxies in the $H - K_s$ sample may be within reach of NIR spectroscopy that could precisely determine redshifts and model stellar populations based on the prominent Balmer/4000 Å breaks, as has been done quite effectively for DRGs at $z \sim 2.5$ (Kriek et al. 2006a). Finally we note that the UKIDSS Ultra Deep Survey is planned to be ~ 0.2 mag deeper than our adopted K_s limit over an area ~ 90 times that of FIRES, which would vastly increase the sample sizes of galaxies selected as described here.

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